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BASEBAND DATA TRANSMISSION USING WIRELINE CABLE

O. Cardinale
W.J. Ciesluk, Jr.

SEPTEMBER 1969

Prepared for

AEROSPACE INSTRUMENTATION PROGRAM OFFICE
ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
L. G. Hanscom Field, Bedford, Massachusetts

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Project 7050
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Bedford, Massachusetts
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FOREWORD

This report was prepared by the Communications Techniques Department of The MITRE Corporation, Bedford, Massachusetts, under Contract F 19628-68-C-0365. The work was directed by the Ground Instrumentation Engineering Division under the Aerospace Instrumentation Program Office, Air Force Electronic Systems Division, Laurence G. Hanscom Field, Bedford, Massachusetts. Robert E. Forney served as the Air Force Project Engineer for the program, identificable as ESD (ESSIC) Project 5932, Range Data Transmission.

REVIEW AND APPROVAL

This technical report has been reviewed and is approved.

GEORGE T. GALT, Colonel, USAF
Director of Aerospace Instrumentation Program Office

ABSTRACT

The feasibility of using baseband signaling techniques for data transmission over multipair wireline cable plant is examined. The limit of transmission distance over 19 AWG and 22 AWG non-loaded wire pairs is determined by computing the eye patterns for polar NRZ signaling at various data rates. Polar NRZ signaling was implemented and tested on existing wireline data transmission links, and results were compared with theoretical predictions. The results showed that significant transmission distances can be achieved by using simple and inexpensive polar NRZ techniques. Other baseband techniques such as bipolar signaling at described and recommended as candidates for extremely long multipair wireline cable links and/ or high data rate transmission.

ACKNOWLEDGMENT

The authors wish to thank Lloyd James, who assembled the test facilities and conducted the field test program.

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SECTION I

A SHORT-HAUL DATA TRANSMISSION PROBLEM

With the growth in complexity of data transmission systems, the need for inexpensive short-haul data links has increased. As a specific example, many data communications systems are configured as a group of remote stations connected to a central data processing complex. Each station contains a number of individual data subscribers scattered throughout its expanse and a centrally located communications control center. The data from the individual subscribers are transferred to the communications center where they are prepared for transmission to the central data processing complex by the station's multiplex and modulation facilities. This configuration eliminates the need for inefficient (by virtue of their low utilization), expensive transmission facilities at each data subscriber location.

To employ this configuration economically, however, the transmission techniques used to transfer the data from the subscriber locations to the communications centers must be simple and inexpensive. At the same time, these techniques must provide sufficient quality over the intra-station links so that the performance of the overall transmission facilities will not be negligibly degraded.

One approach is to connect the data subscribers to the communications center with non-loaded wire pairs and employ signaling techniques for data transfer which require minimal shaping and/or processing. Two data transmission techniques which are candidates for this application are carrier data transmission (inexpensive data modems designed for short haul) and baseband data transmission. Carrier techniques have been widely used, and there is no doubt as to their suitability. On the other hand, the use of baseband techniques

for this application has not been widely employed, yet they promise to lead to simple and inexpensive implementations. The purpose of this paper, then, is to examine baseband transmission techniques for digital data transmission over simple wire-pair transmission networks.

SECTION II

THE USE OF BASEBAND SIGNALS

The use of baseband signals for short-haul data transmission appears to be attractive, since their implementation is relatively simple and inexpensive. The most elementary approach is to transmit the signal that emanates from the subscriber's data source after minimal shaping and processing. Presently, many systems use polar Non Return to Zero (NRZ)* signals at the low level dc interfaces. The power spectrum of an idealized polar NRZ signal for a random data sequence is well known to be:[1]

$$\Phi_P(f) = \left[VT \frac{\sin(\pi fT)}{\pi fT}\right]^2 \quad (1)$$

where V is the peak amplitude and T is the duration of one bit. The transmission of this signal over non-loaded wire pairs is the primary consideration of this paper. The polar NRZ signal and its spectrum are shown in Figure 1.

THE CHANNEL

The transmission plant which is the most desirable to connect the data subscribers to the communications center is non-loaded wire pairs, particularly 19 AWG and 22 AWG gauge because of their relatively low cost. These pairs are usually installed as multi-pair telephone cable consisting of unshielded non-loaded wireline pairs separated into several sheaths each containing a group of pairs. The cables are generally direct

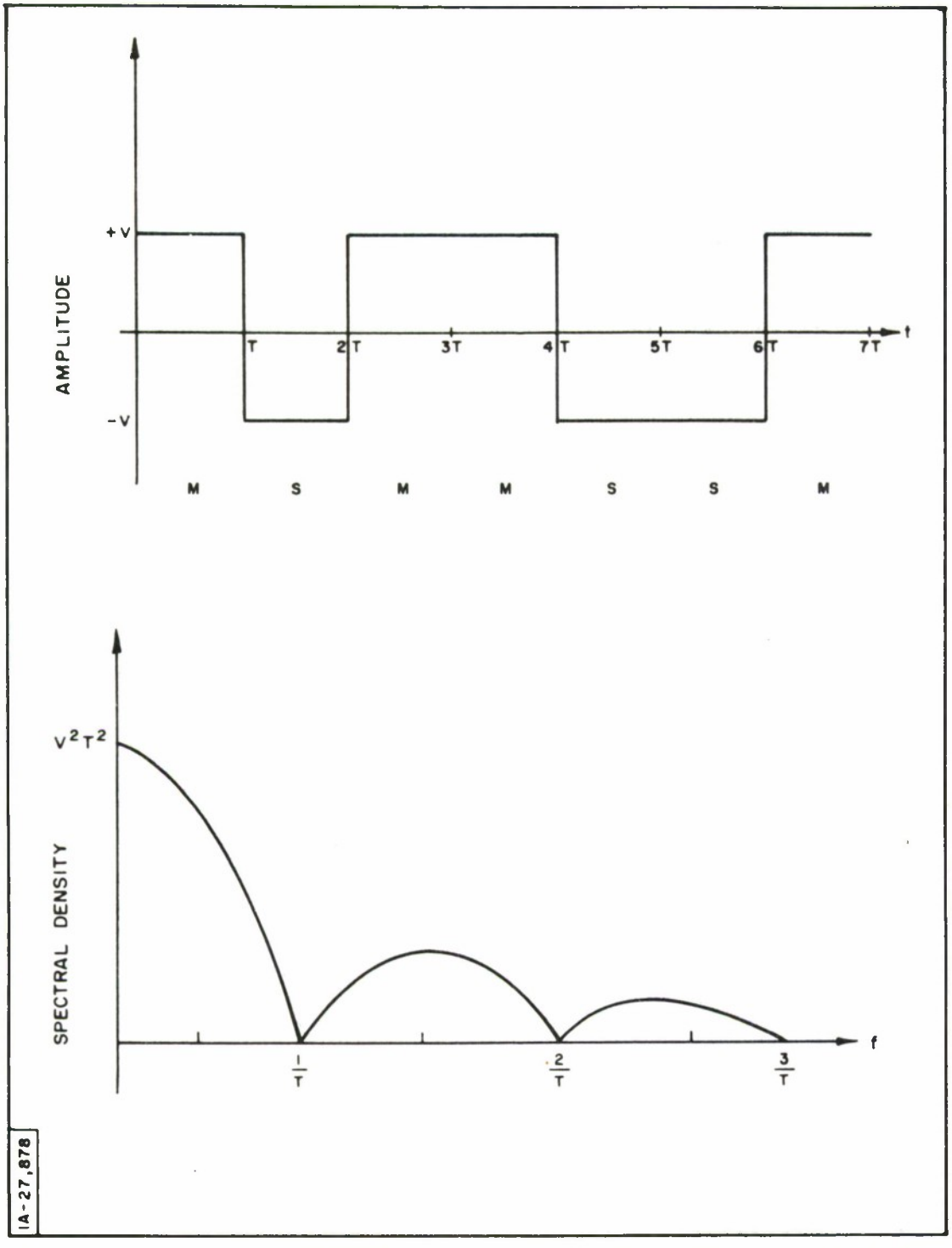

Figure 1 Polar NRZ Signal and Its Power Spectrum

burial types, but some may have to be installed above ground in rocky terrain. These cables have been used to transmit telephone and teletype simultaneously with the data from the subscribers to the communications center. A summary of the electrical parameters of 19 AWG and 22 AWG non-loaded wireline pairs is shown in Table I.

Table I

Electrical Parameters of Non-Loaded Wire Pairs[2]
(at 1 kHz)

	Resistance (ohms/ loop mile)	Conductance μmhos/ loop mile	Inductance (mH/ loop mile)	Capacitance (μF/ loop mile)
22 AWG	166.0	2.1	1.00	0.083
19 AWG	84.0	1.0	1.111	0.0609

*From Reference 2, measured at 1 kHz.

TRANSMISSION CHARACTERISTICS OF NON-LOADED WIRELINE PAIRS

Conventional transmission line theory can be used to determine the transmission characteristics of non-loaded wireline pairs. The response E_x/E_s of an infinitely long or matched non-loaded transmission line at a distance x from the sending end is given by:[2]

$$\frac{E_x}{E_s} = e^{-\gamma x} = e^{-(\alpha + j\beta)x} = |e^{-\alpha x}|\, e^{-j\beta x} \qquad (2)$$

where γ, α, and β are functions of the transmission line parameters R, G, L, and C, the resistance, conductance, inductance, and capacitance

per unit length, respectively. A matched line is loaded with the characteristic impedance of the line, which is given by

$$Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad . \tag{3}$$

With this loading maximum power is transferred to the load.

The propagation constants α and β are plotted as a function of frequency in Figure 2. The graph shows that for increasing frequency α approaches a constant and β approaches linearity, which (referring to Equation 2) are the conditions for distortionless transmission. At the same time the characteristic impedance approaches a purely resistive component of constant value, namely $\sqrt{L/C}$.*

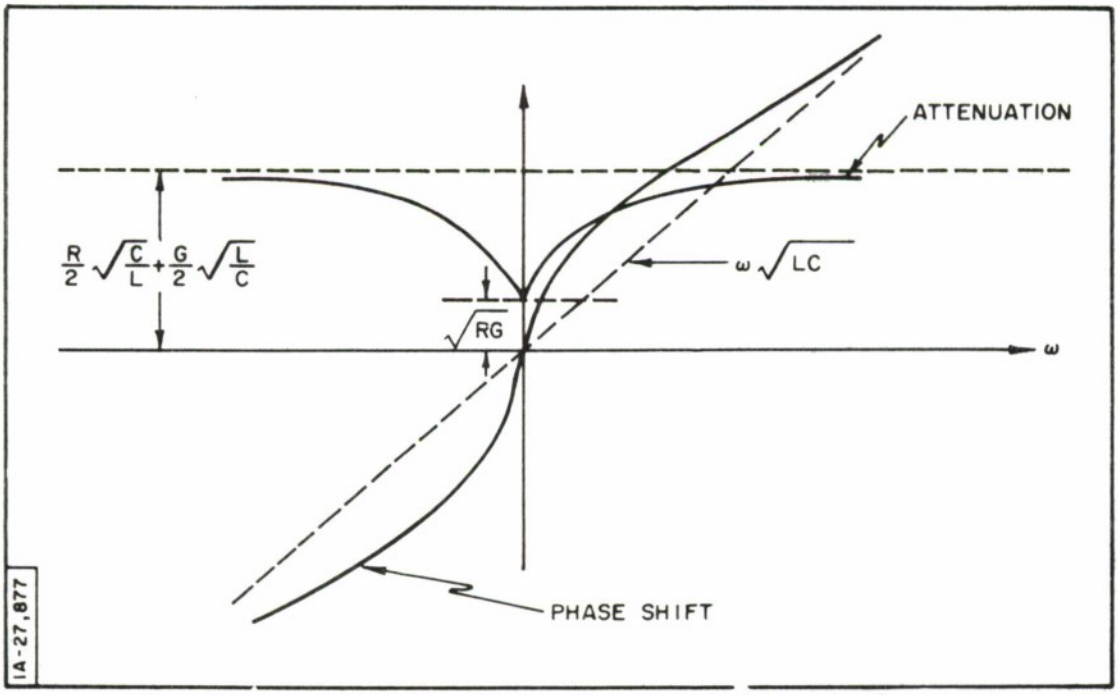

Figure 2. Frequency Dependence of Transmission Line Propagation Constants

*Of course, this assumes that the electrical parameters of the line are independent of frequency. In practice, however, the resistance R increases with frequency predominantly because of the skin effect. For the frequencies of interest in this report, the increase in resistance due to this effect has negligible influence on the results.

From this brief review of transmission line theory it is clear that the predominant signal distortion occurs in the lower frequency signal components. As a consequence the polar NRZ signal will be highly susceptible to this distortion, since the peak of its signal is at dc.

A network which has an input impedance equal to Equation (3) or a network which would equalize non-loaded wire pairs is a complex synthesis and would defeat the purpose of providing an inexpensive transmission system. The approach here is to load the wire pairs and match the driving source with the nominal resistive characteristic impedance of the line, and utilize the transmission plant up to the limit of intolerable distortion. The response E_x/E_s of a non-loaded wireline pair used in this way is[2]

$$\frac{E_x}{E_s} = \left\{ \left(1 + \frac{Z_s}{Z_o}\right)\left(\frac{Z_L + Z_o}{2Z_L}\right) e^{\gamma x} - \frac{(Z_L - Z_o)(Z_s - Z_o)}{Z_s + Z_o} e^{-\gamma x} \right\}^{-1} \quad (4)$$

where the source impedance Z_s and load impedance Z_L is a resistance equal to $\sqrt{L/C}$. The attenuation and delay response of 22 AWG wireline pairs operated in this way as a function of transmission distance are shown in Figures 3 and 4.

THEORETICAL PULSE RESPONSE OF NON-LOADED WIRELINE PAIRS

The first step is to determine the transmission limit of these wire pairs due to the signal distortion. This was performed in the following manner. First, the pulse response of 19 AWG and 22 AWG non-loaded wireline pairs terminated at its source and sink with its nominal characteristic impedance was determined for the polar NRZ pulse of Equation (1) using

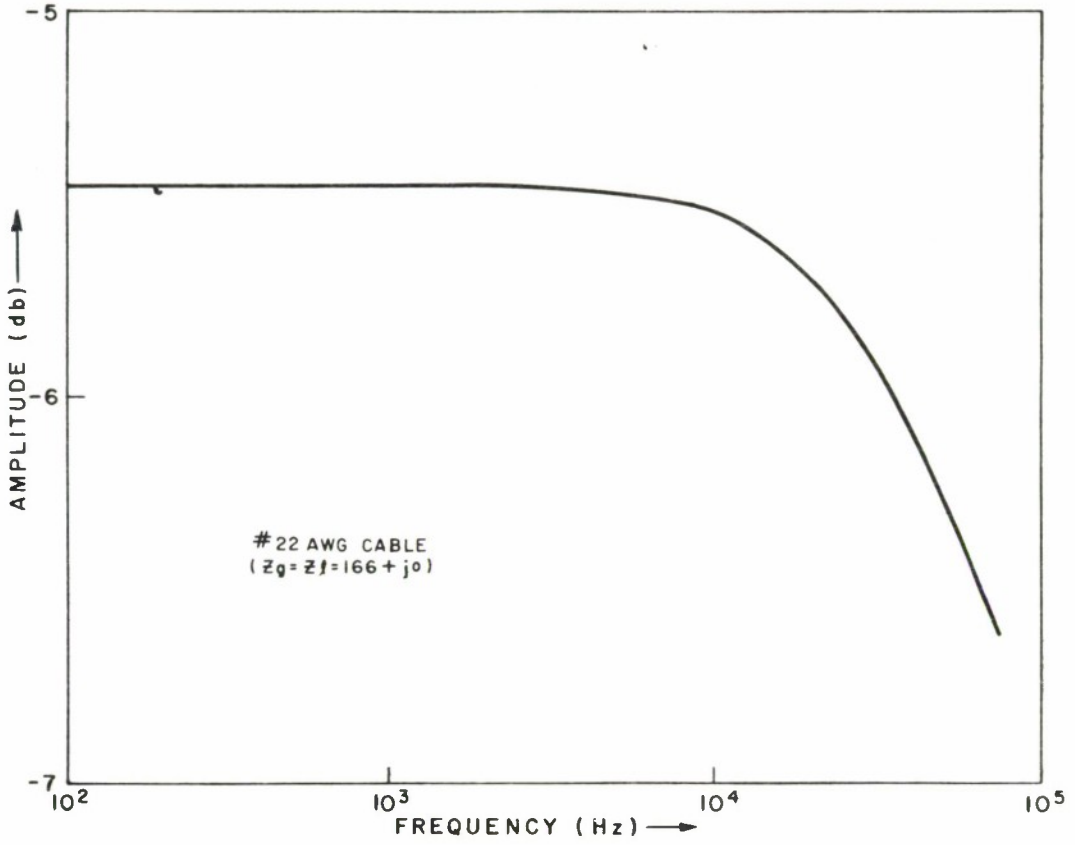

Figure 3. Transmission Line Response, Amplitude vs. Frequency

(a) x = 1 mile

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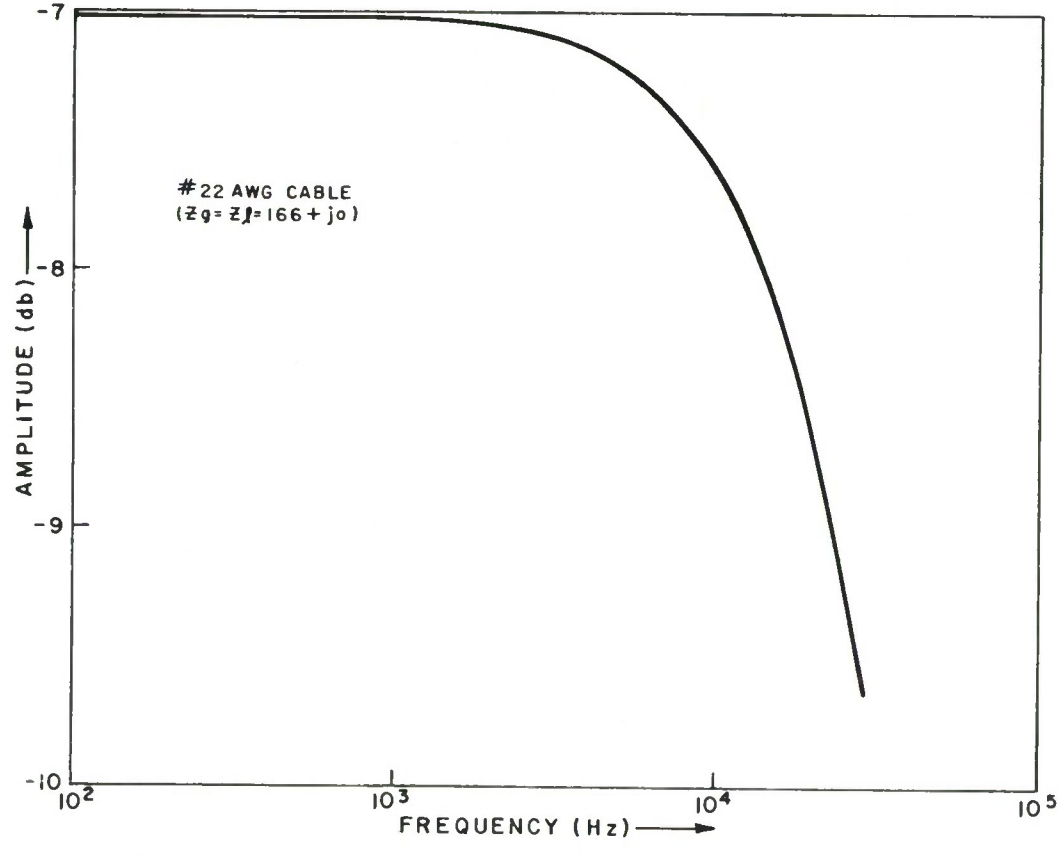

Figure 3. (Continued)

(b) x = 2 miles

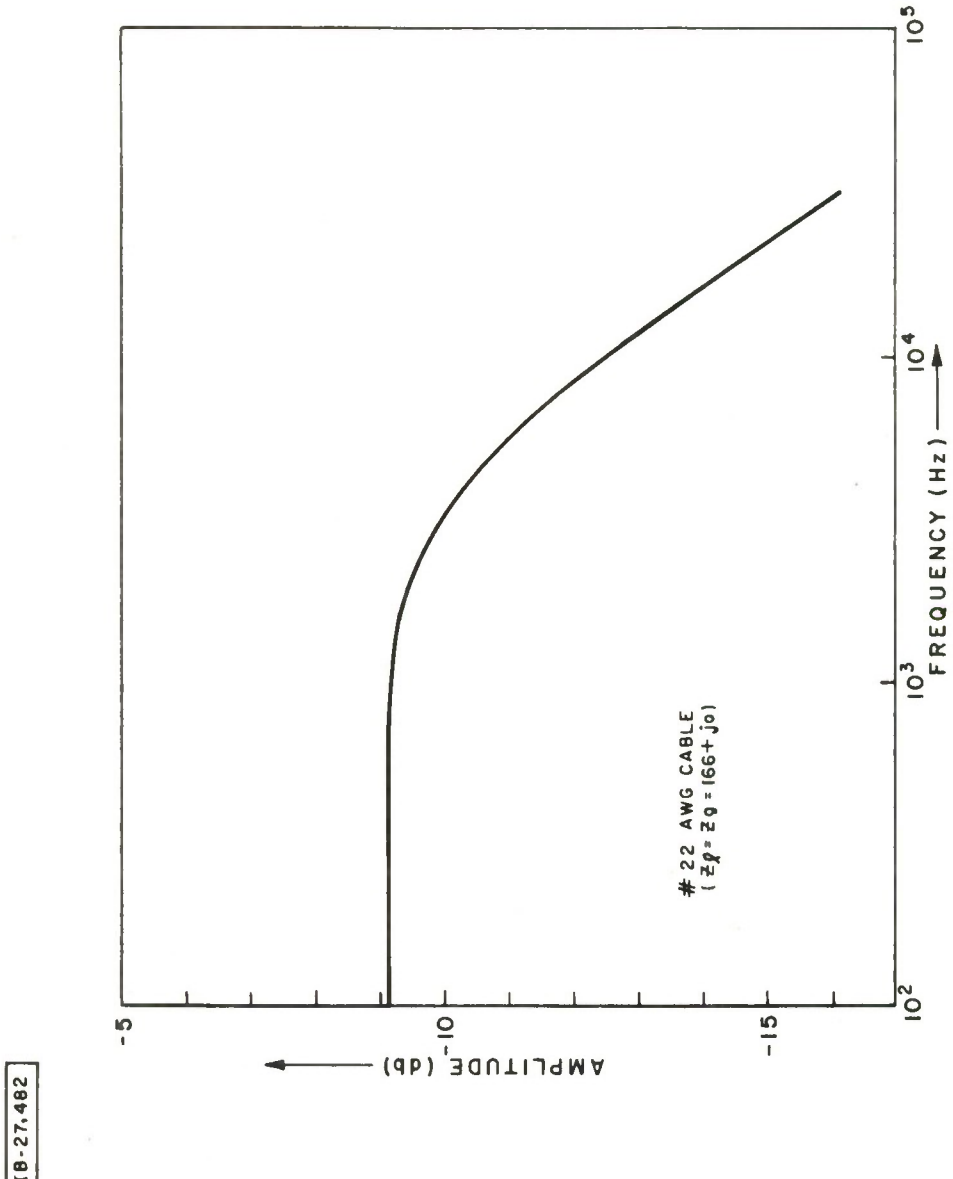

Figure 3. (Continued)

(c) x = 4 miles

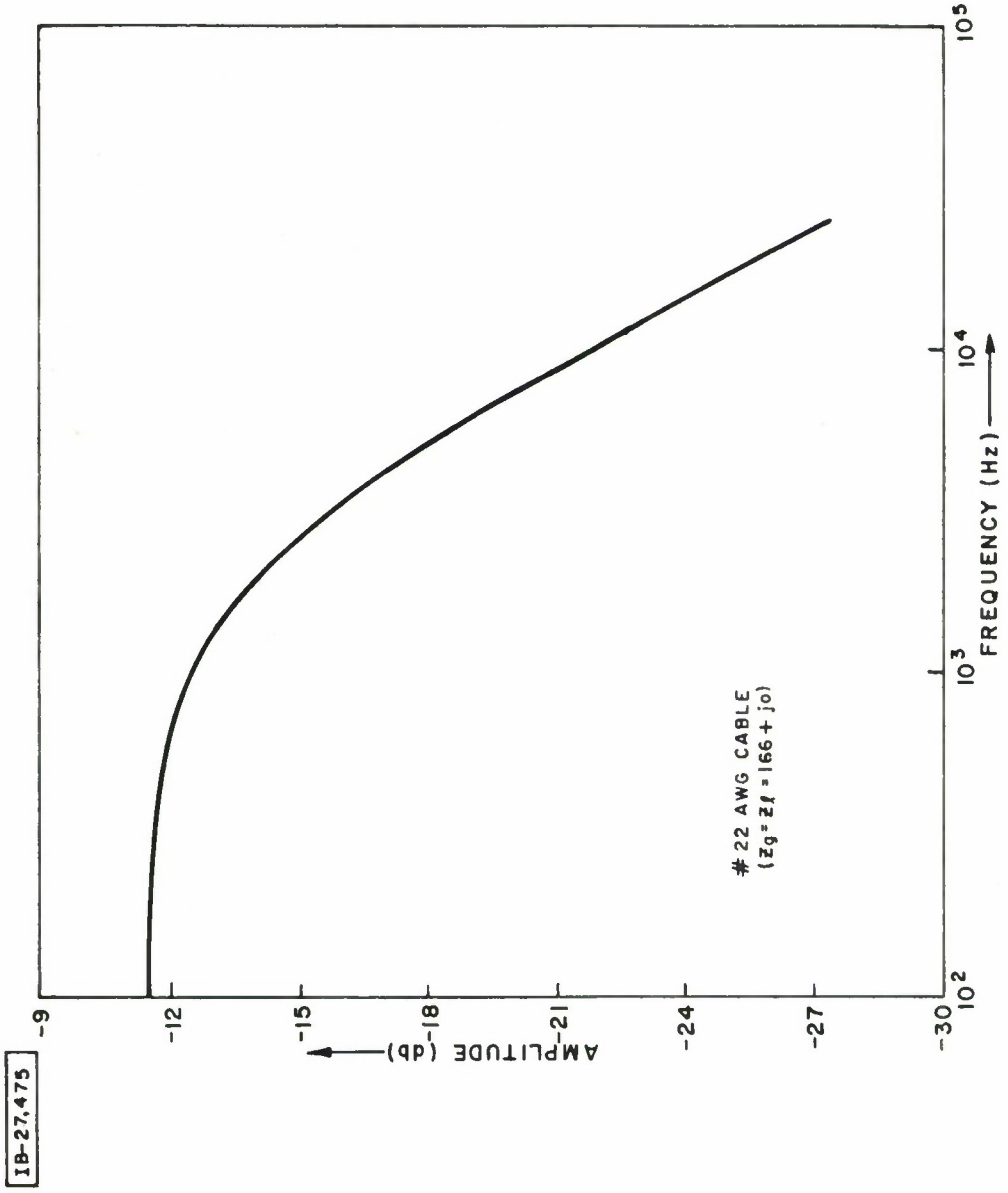

Figure 3. (Continued)

(d) x = 8 miles

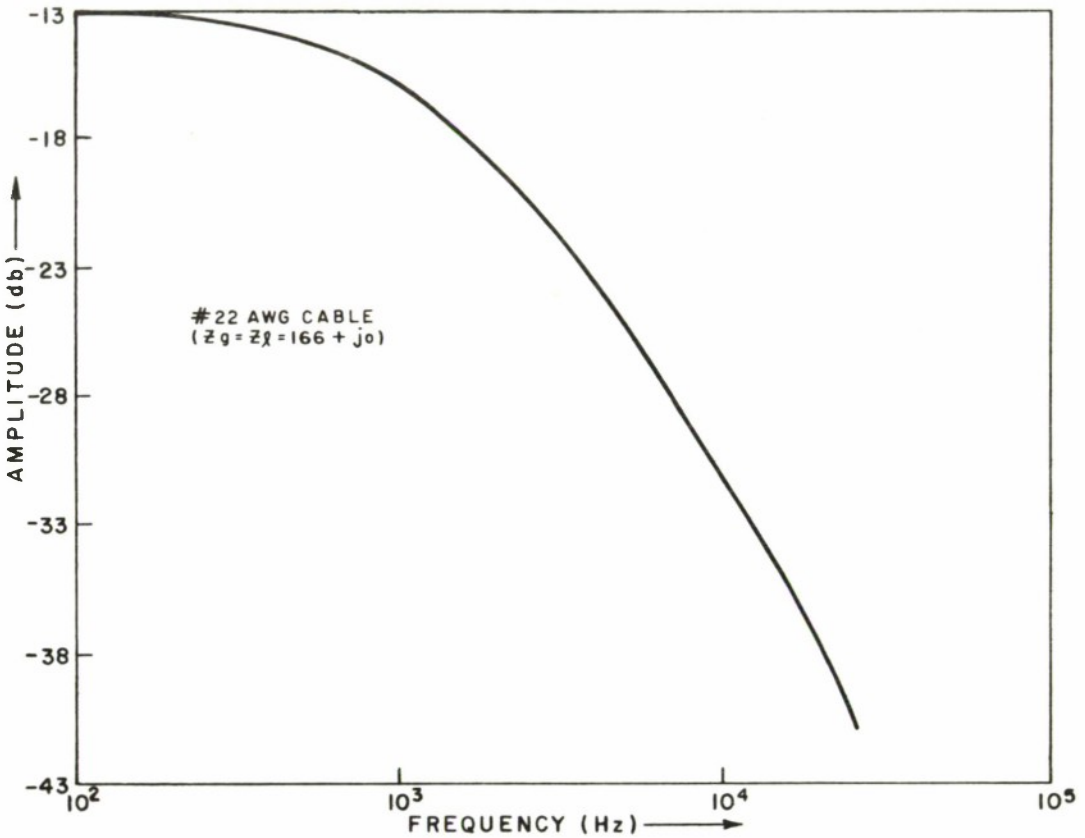

Figure 3. (Continued)

(e) x = 12 miles

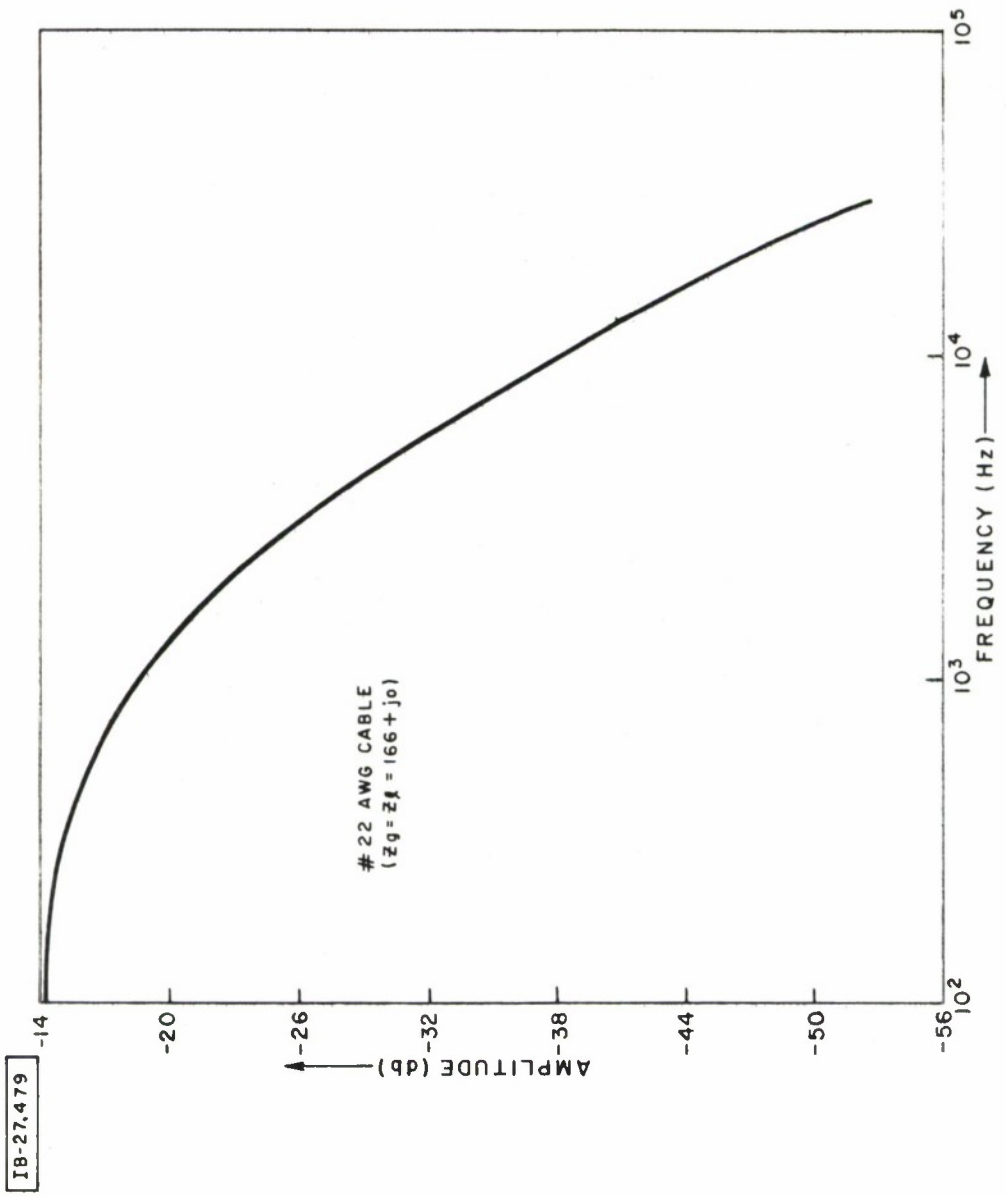

Figure 3. (Concluded)

(f) x = 15 miles

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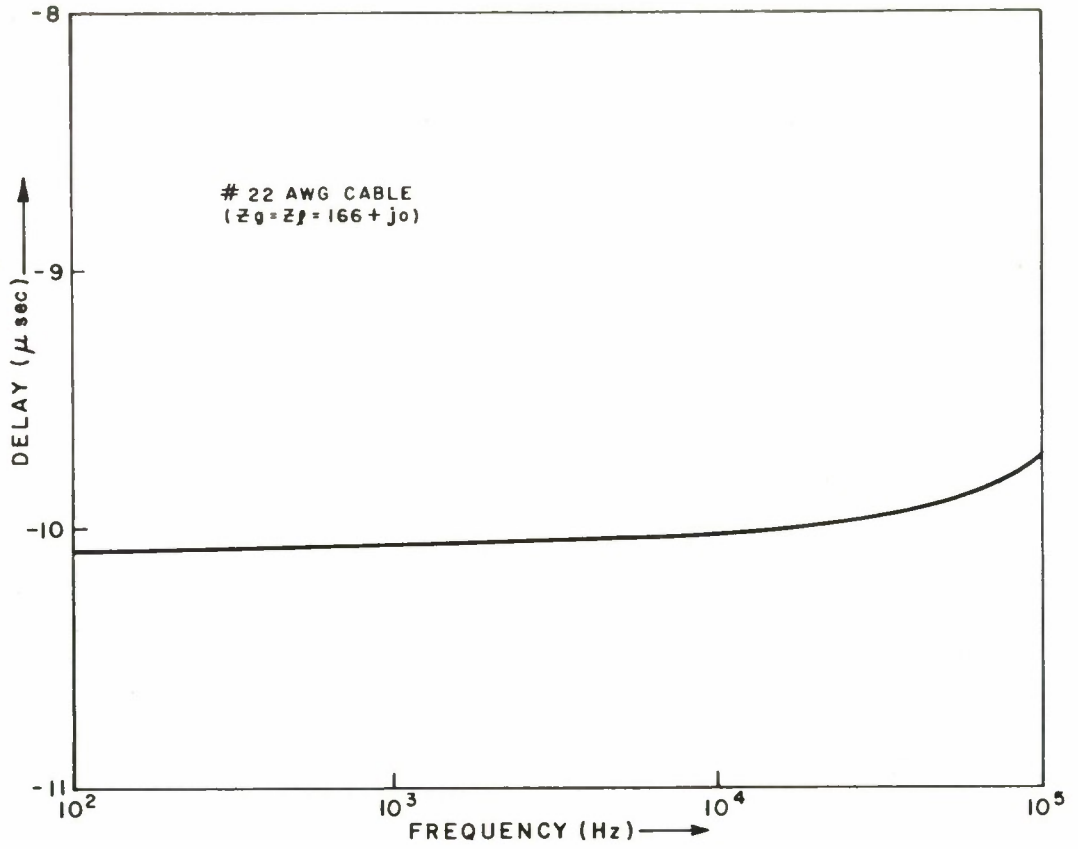

Figure 4. Transmission Line Response, Delay vs. Frequency

(a) x = 1 mile

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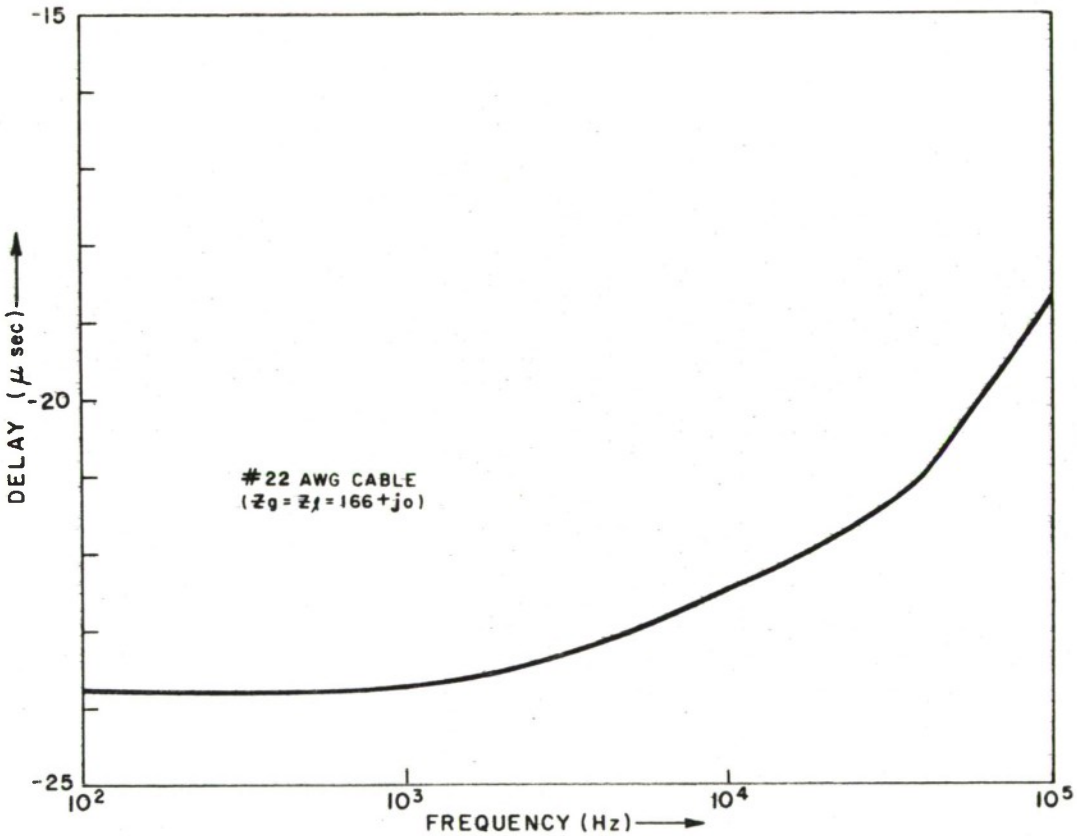

Figure 4. (Continued)

(b) x = 2 miles

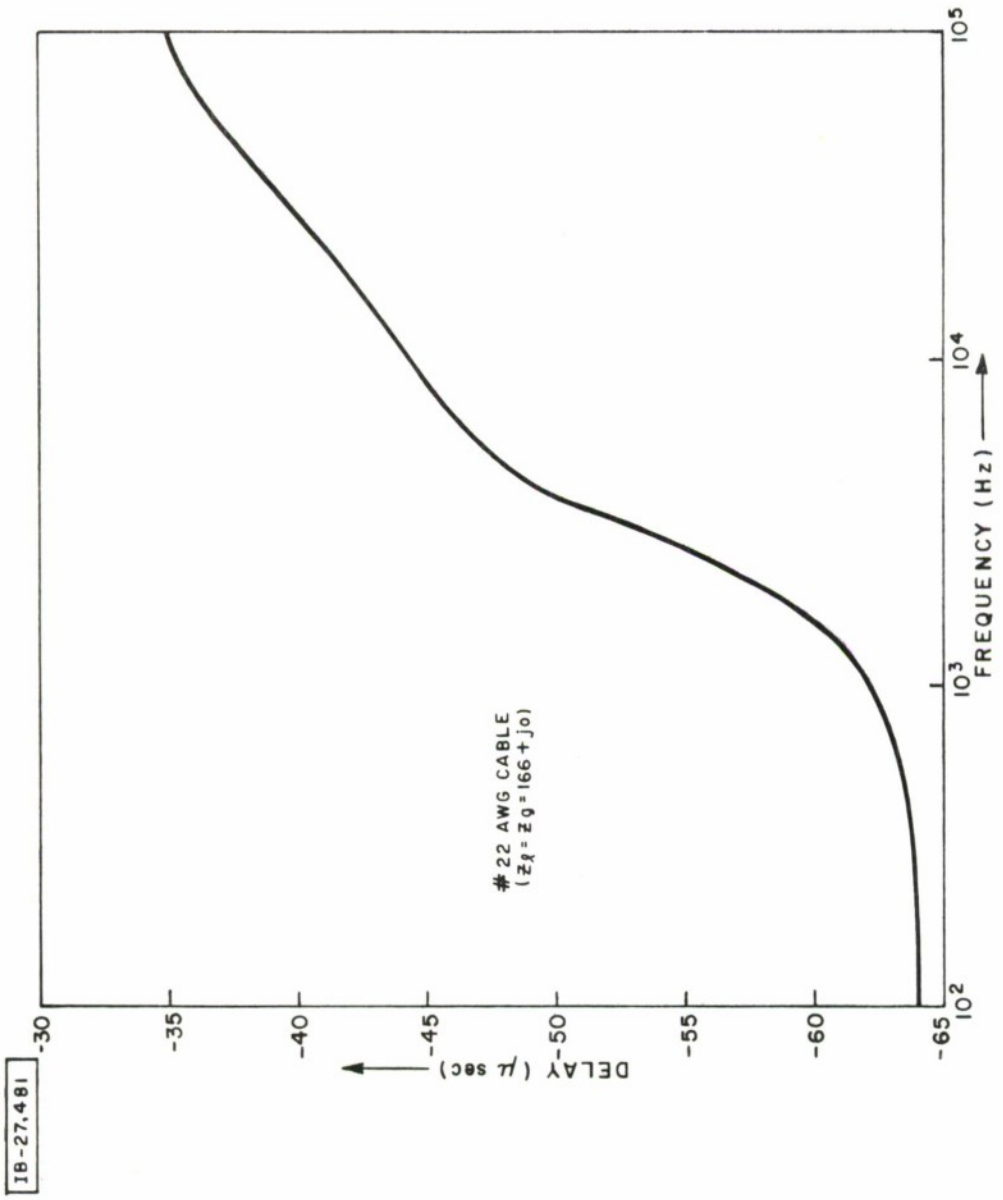

Figure 4. (Continued)

(c) $x = 4$ miles

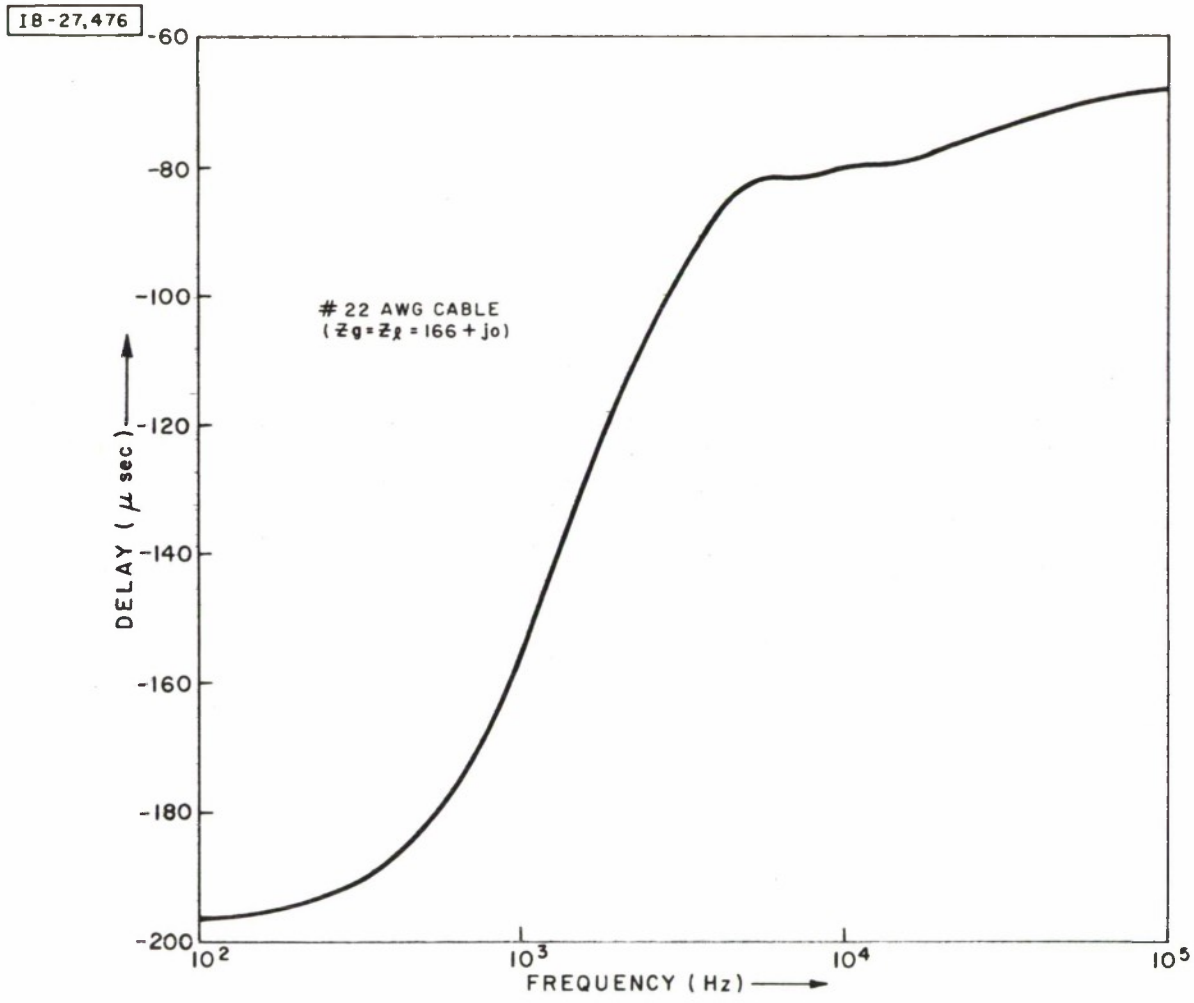

Figure 4. (Continued)

(d) x = 8 miles

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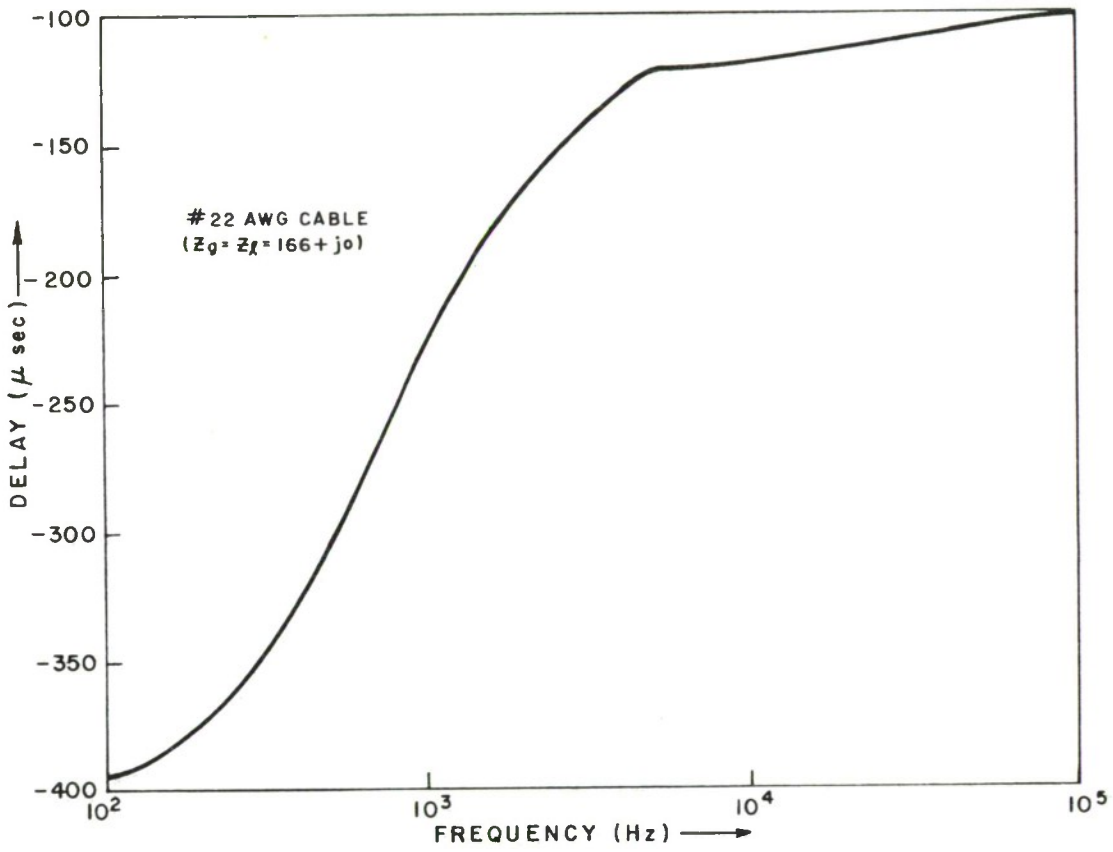

Figure 4. (Continued)

(e) x = 12 miles

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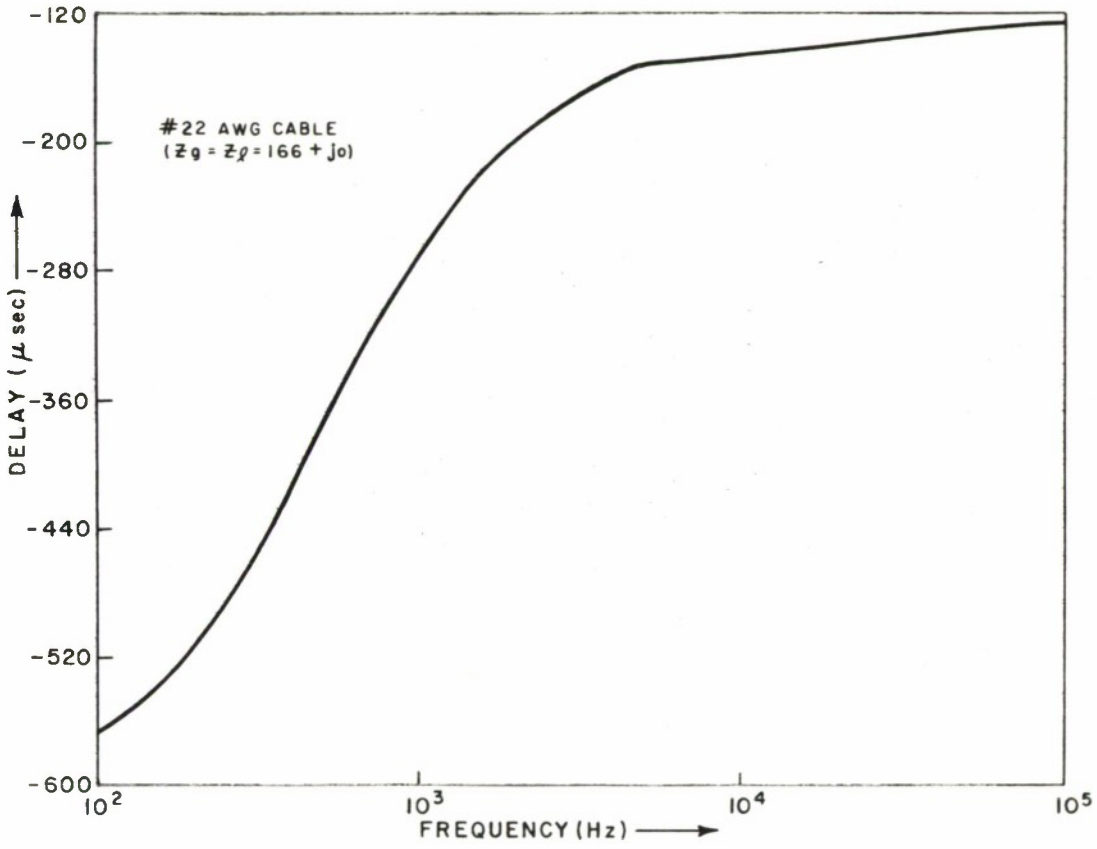

Figure 4. (Concluded)

(f) x = 15 miles

Equation (4), the line parameters of Table I, and a Fast Fourier Transform (FFT) computing routine. The pulse widths were selected to correspond to pulse rates of 2.4, 9.6, and 40.8 kb/s. Next, the eye patterns[1] representing the maximum (peak) distortion experienced by a pulse in a sequence preceded and followed by 32 other pulses were computed. The results are displayed in Figures 5 through 8. Figures 7 and 8 show the percent of peak eye opening with respect to the amplitude of a pulse not affected by intersymbol interference as a function of distance for 22 AWG and 19 AWG non-loaded pairs respectively. The result shows that the eye pattern is still open out to 18 miles for a 2.4 kb/s signal and 5 miles for a 40.8 kb/s signal over 19 AWG wire pairs. The relative magnitude of the peak eye opening for these curves is shown in Figures 5 and 6.

OTHER TRANSMISSION IMPAIRMENTS

There are additional factors besides the distortion already discussed which will impair baseband data transmission over multipair wireline cable plant. The additive effects of noise, crosstalk, and rfi in these multipair cables can hinder baseband data transmission if they are present with sufficient power to cause incorrect recognition of the bits.

The thermal noise levels on these links are expected to be insignificant. However, if switching is a function in the system, impulse-type noise caused primarily by induced switching transients from adjacent cable pairs may be significant. In addition, crosstalk and interference from external sources (rfi) can be significant in the multiconductor pairs used for short-haul transmission plant.

Two types of crosstalk can be differentiated in multiconductor cables, namely, near end and far end. The near end crosstalk effect occurs when

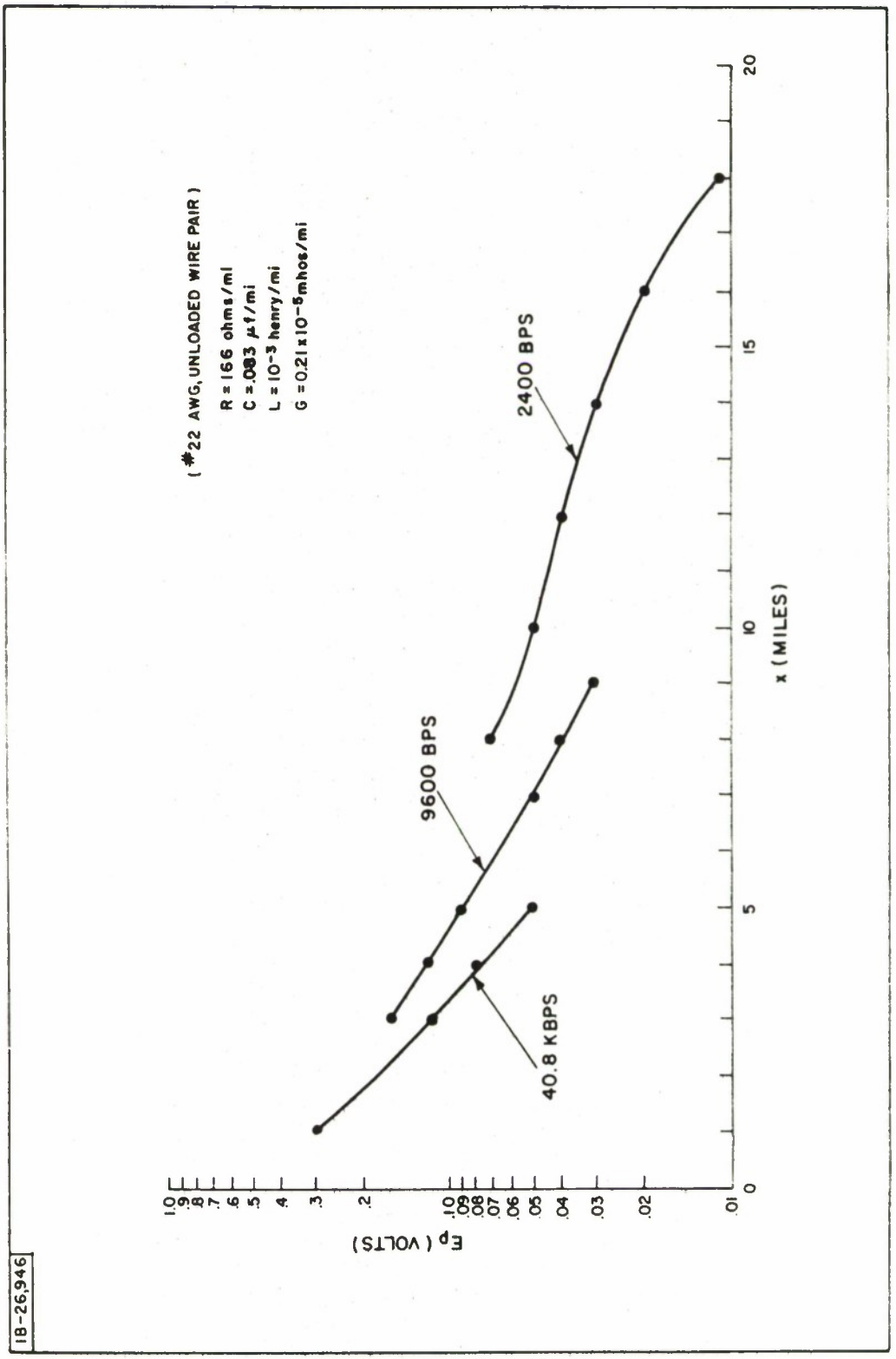

Figure 5. Received Pulse Amplitude vs. Transmission Line Length (No. 22 AWG)

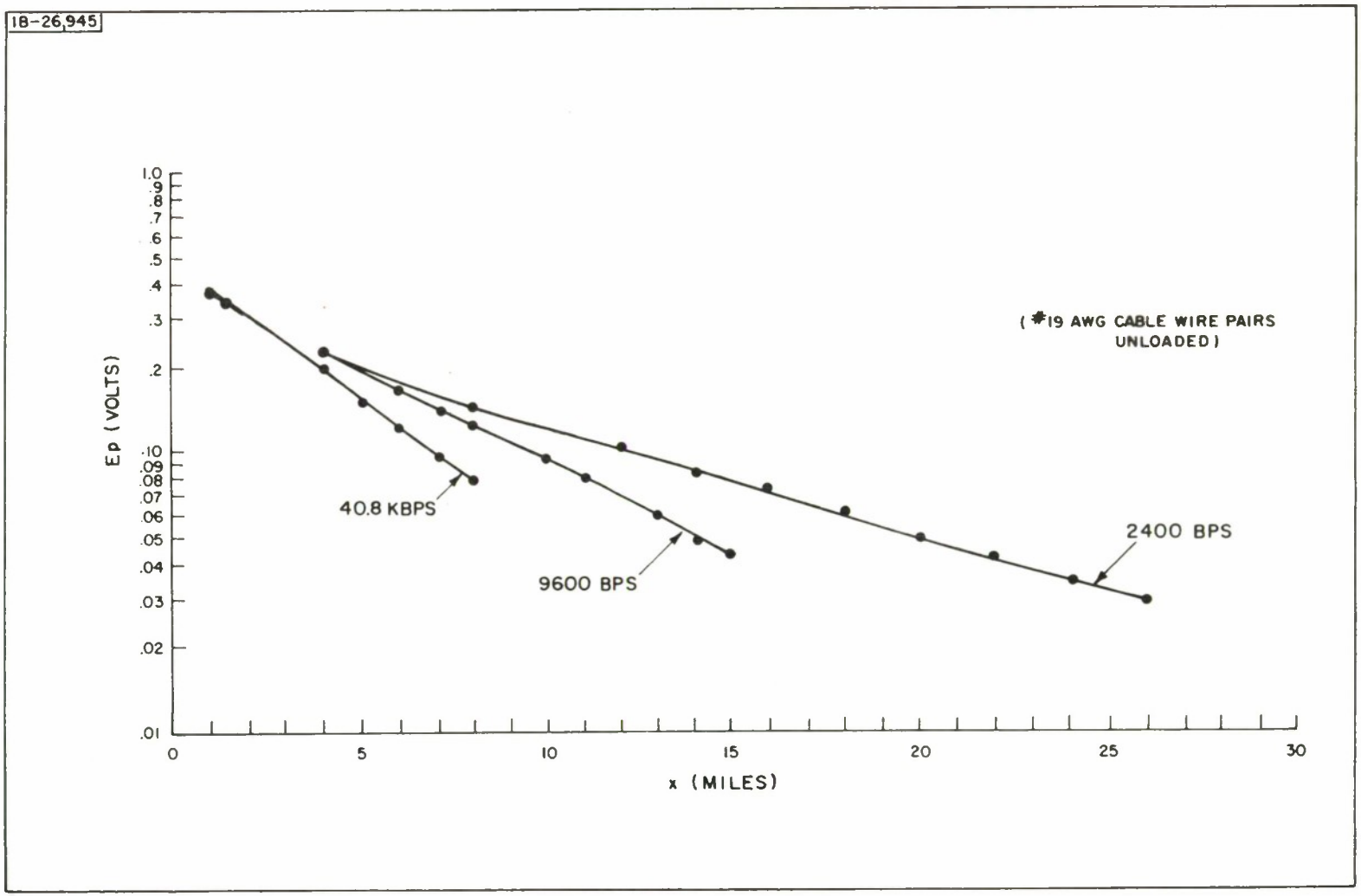

Figure 6. Received Pulse Amplitude vs. Transmission Line Length (No. 19 AWG)

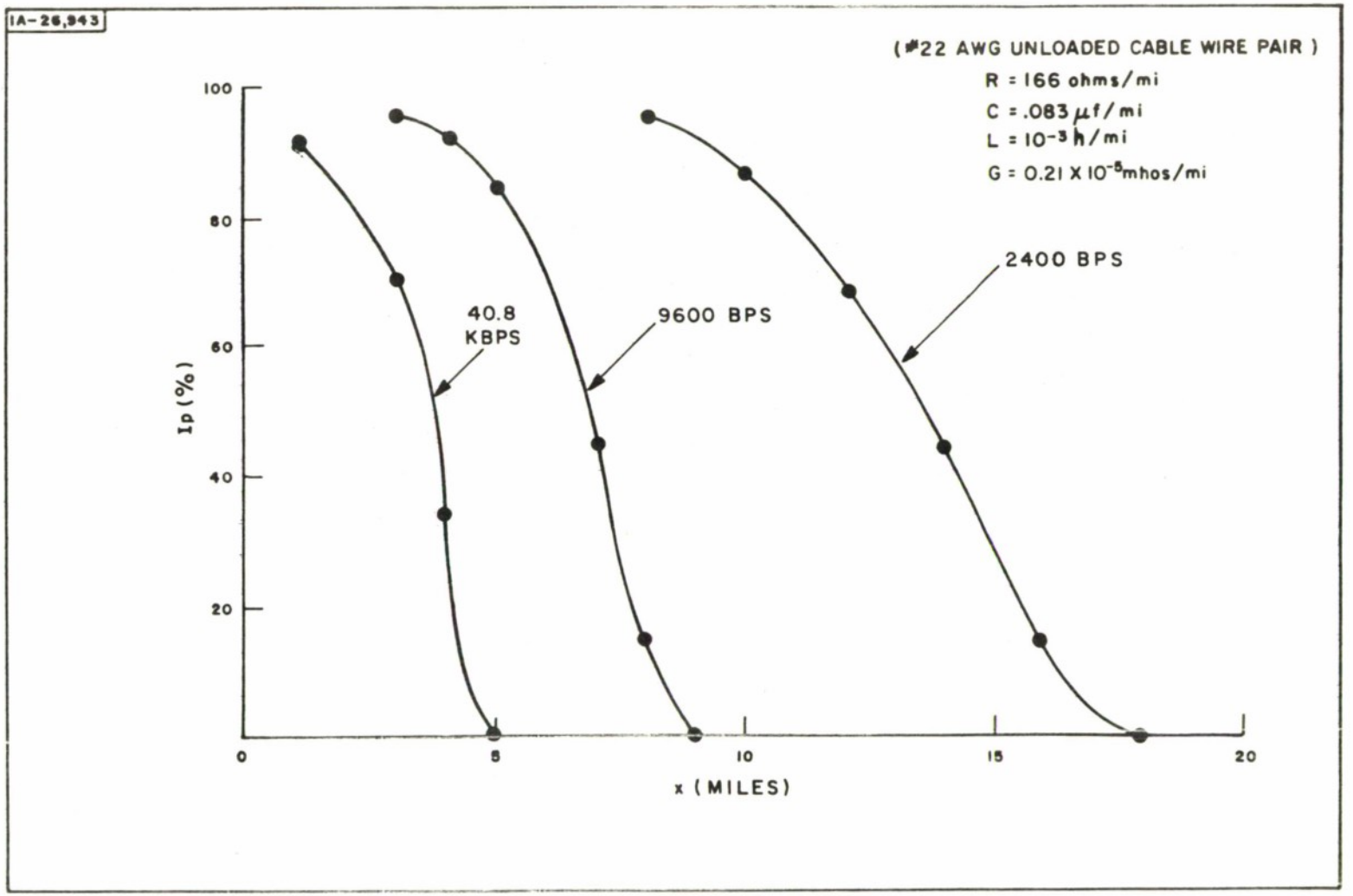

Figure 7. Received Pulse Peak Eye Opening vs. Distance (No. 22 AWG)

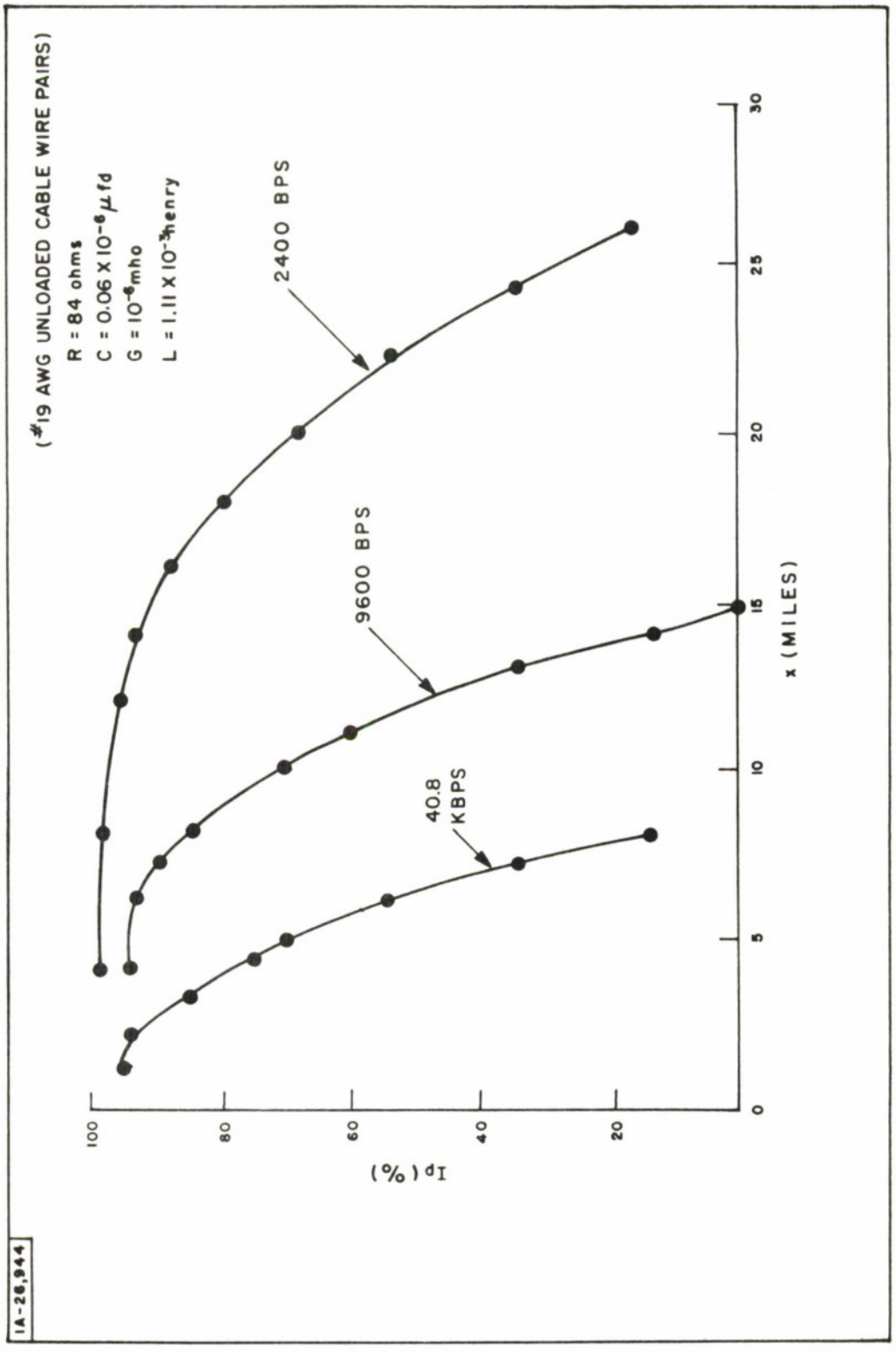

Figure 8. Received Pulse Peak Eye Opening vs. Distance (No. 19 AWG)

a multiconductor cable is used for two-way transmission in which the high-level signal input to the lines cause interference in the adjacent line low-level output signal. The near-end crosstalk levels are independent of line length.

On the other hand, far-end crosstalk levels are due to cumulative capacitive coupling to adjacent pairs along the length of line, and therefore these levels increase with line length. For short segment lines near-end effects will be the predominant crosstalk interference.

SECTION III

SIMPLE BASEBAND DATA TRANSMISSION SYSTEMS

The preceding theoretical investigation shows that polar NRZ signals can be transmitted over useful distances with insignificant signal spectrum shaping and line conditioning. However, to employ this technique cost-effectively transmission configurations must be engineered which are relatively simple and inexpensive compared to carrier techniques.

SYSTEM CONFIGURATIONS

Two simple duplex communications systems which utilize polar NRZ keying at baseband over non-loaded wireline pairs are shown in Figures 9 and 10. They represent the transmission system between a data subscriber at one station and another data subscriber or processor at another station. The polar NRZ signaling is used from the data subscriber locations to the communications centers.

In the first system the data source transmits polar NRZ through a line driver unit, wire pair, and line termination unit to the modulator input of the "transmit" modem at the local communications center. The word generator is timed by the modem's master clock which is transmitted through an identical line driver unit, wire pair, and line termination unit. The modem converts the polar NRZ signal to analog and transmits it over the long-haul transmission plant to a receive modem at the other communications center. The demodulated output and derived clock from the receive modem are transmitted over separate channels consisting of a line driver unit, wire pair, and line termination unit respectively to the data sink. Here the data are regenerated to interface with the sink logic.

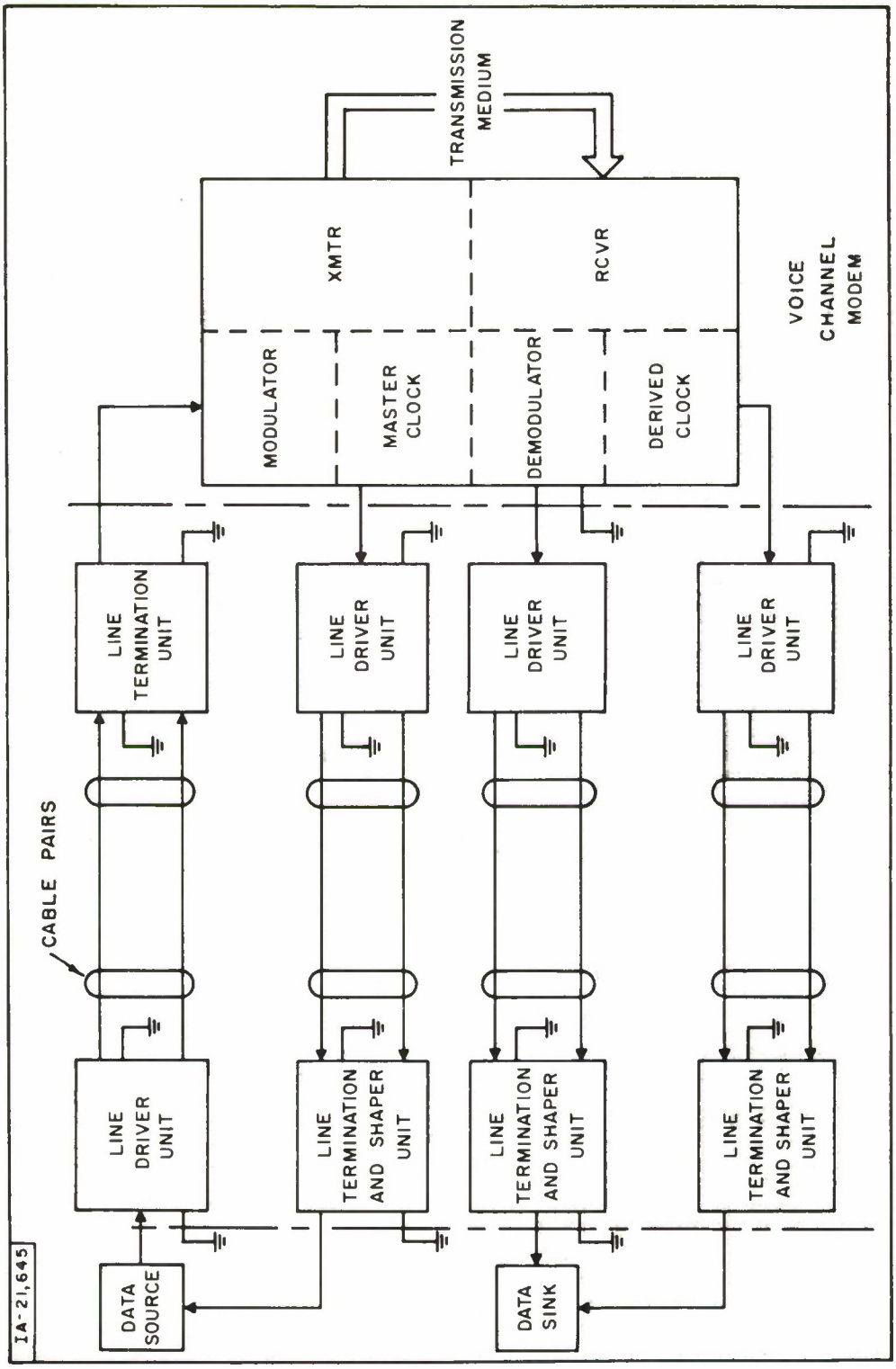

Figure 9. A Simple Baseband Data Transmission System

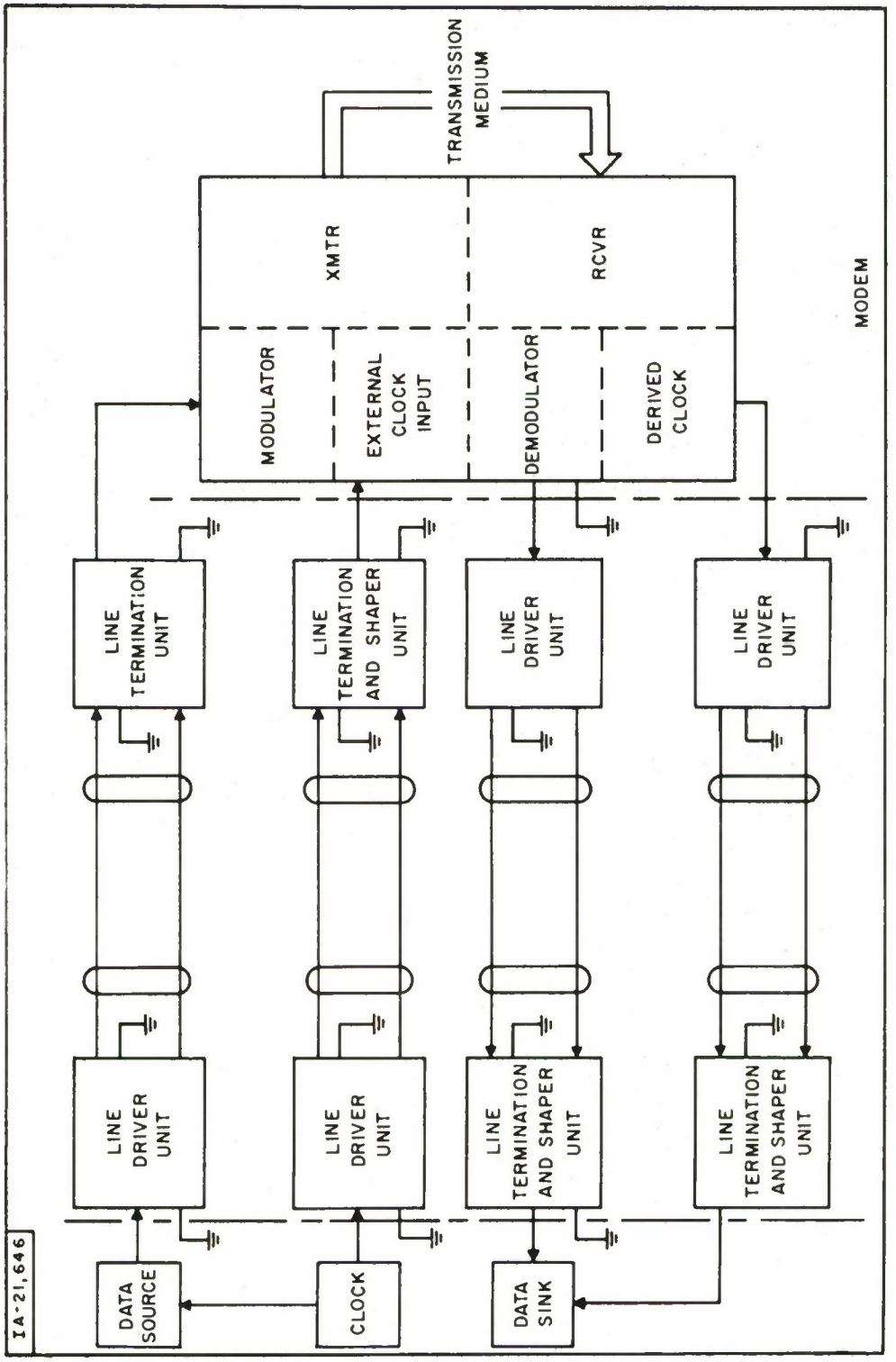

Figure 10. An Alternative Simple Baseband Data Transmission System

The second system differs from the first in that a clock is located at the data source and must be transmitted along with the data to the transmit modem over separate pairs.

The predominant noise, if present, in the intra-station lines will be induced noise and crosstalk. An effective technique available to combat this type of interference is to balance the lines, i.e., employ common-mode rejection. With this technique, crosstalk rejection ratios of greater than 50 dB are readily obtained. In addition, currents due to unequal ground potentials at different ends of the channel will be rejected to the same degree.

No elaborate matching or equalizing network is proposed. Again the approach suggested here is to drive the line with a source whose input impedance is nearly equal to the resistive component of the nominal characteristic impedance of the line, terminate the line with the same, and accept the resultant residual distortion.

The line driver and termination units can take on any of several simple implementations. The purpose of the line driver unit is to accept the unbalanced output from the data source and present a polar NRZ signal to the balanced line and match the source and line impedances. The purpose of the line termination unit is to receive the distorted polar NRZ signal from the line, regenerate it, match the line to the sink, and present the regenerated signal to the unbalanced sink. The line termination unit can be developed around a slicer circuit or a comparator circuit which detects the peaks of the pulses and samples them with the reference clock. Usually the input to the modem modulator is implemented with such a comparator circuit.

EVALUATION OF THESE SYSTEM CONCEPTS

To determine the suitability of the system concepts just proposed for short-haul data transmission, a test configuration stressing simplicity of implementation was constructed and tested on existing multiconductor pairs at USAF Eastern Test Range (Cape Kennedy). The system was operated with various lengths of 19 AWG wireline pairs and error rate measurements were recorded. The objective of the test was to establish the maximum transmission distance for low-level MIL-STD-188B polar NRZ baseband data at 2400 b/s over 19 AWG non-loaded pairs with the proposed systems.

The test configuration used for the tests is shown in Figure 11. The unipolar NRZ output of a word generator is converted to polar NRZ in a driver buffer and transmitted through a line driver, wire pair, and line termination unit to the modulator input of a voice channel wireline modem.* The word generator is timed by the modem's master clock which is transmitted through an identical line driver unit, wire pair, and line termination unit and shaped in a slicer buffer. The system error rate is measured by connecting the modem back-to-back and synchronizing and comparing the modem demodulator output to the local word generator. The bit errors are then recorded on a counter. The error-counting circuitry is timed by the modem-derived clock.

The line driver unit consists of a pulse amplifier and an audio transformer which provides a method of driving the line in a balanced mode with an unbalanced driver. The line termination unit is simply another audio transformer terminated with a resistor. Again, the transformer provides

*The wireline modem which was used in this test is the AN/GSC-20. It is a four level time differential PSK system which uses 4 tones to achieve data transmission rates up to 2400 b/s. The tones are spaced 600 Hz apart beginning at 900 Hz and ending at 2700 Hz. Each tone channel is keyed at 300 symbols per second (baud with 2 bits/symbol) resulting in a transmitted symbol duration of 3 1/3 milliseconds.

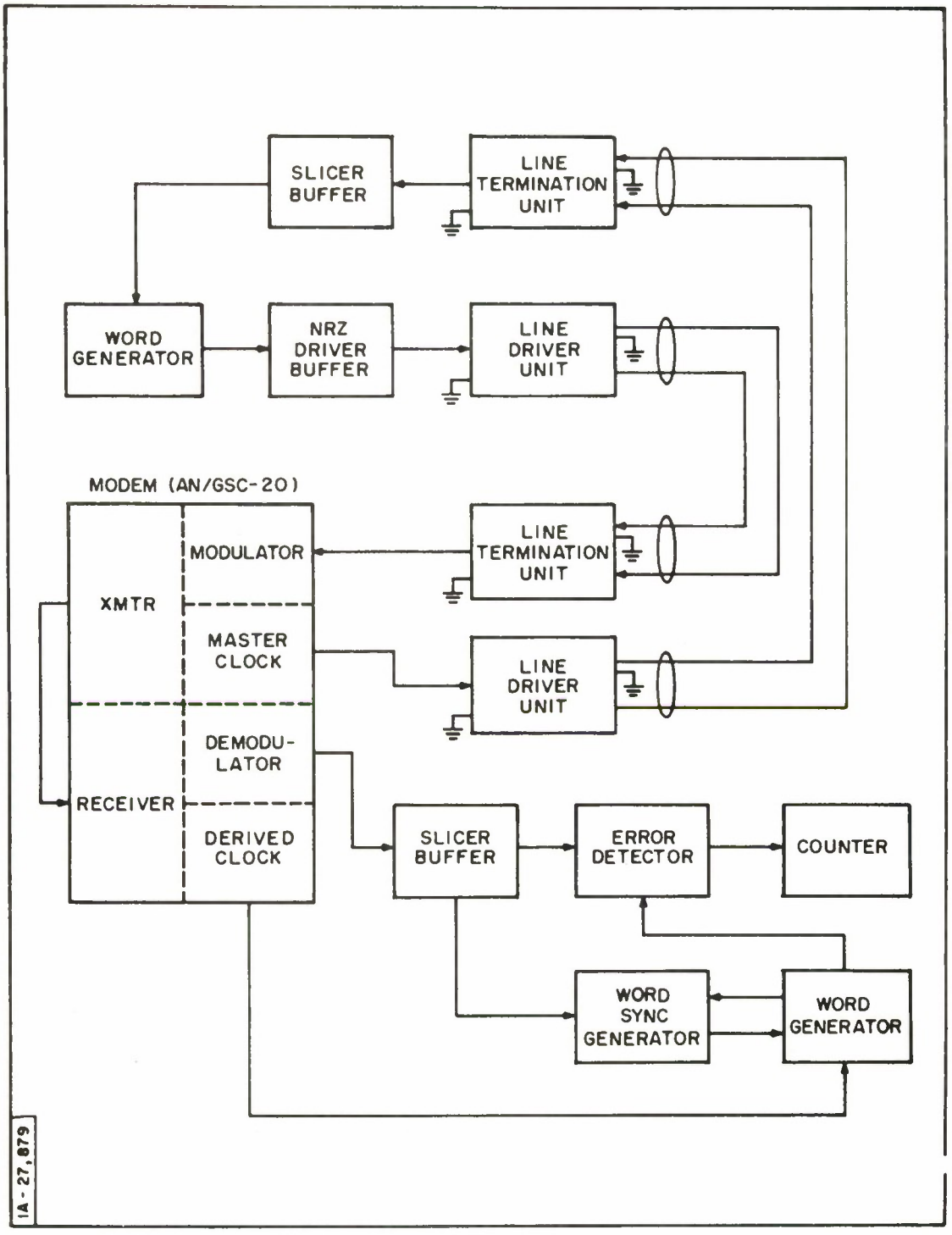

Figure 11. Baseband Data Transmission System Test Configuration

a method of driving the unbalanced input of the modem modulator from the balanced line. The transformers were ordinary high-quality, audio interstage coupling transformers. The electrical balance obtained with these devices was measured in the laboratory and the following performance was observed,

66 dB rejection against 1 kHz sine wave

44 dB rejection against thermal noise (20 kHz)

25 dB rejection against thermal noise (500 kHz)

The tests were conducted over 19 AWG wireline loops of 8, 11, 13, and 16 miles for periods of at least 5 consecutive hours. The system was operated error-free at 2400 b/s over the 8- and 11-mile loops. On the 13-mile loop occasional bursts of errors occurred during the test, but the test engineer noted a loss of timing signal on occasion. On the 16-mile loop, bursts of errors were intolerably frequent. The error rate was much worse than 1 in 100. Oscillographs of the data (upper trace) and output signals (lower trace) for the various tests are shown in Figures 12 through 15. Crosstalk levels measured with an unbalanced instrument were below -50 dBm.

Although operationally useful transmission distances were achieved during these tests, they were considerably less than the theoretical predictions presented in Section II. This discrepancy between actual and theoretical transmission distances is caused by non-standard installation practices such as insertion of splices for multiple access to cable pairs. Such practices are common on the test ranges. With cable plant installed free of these practices, considerably longer transmission distances can be expected.

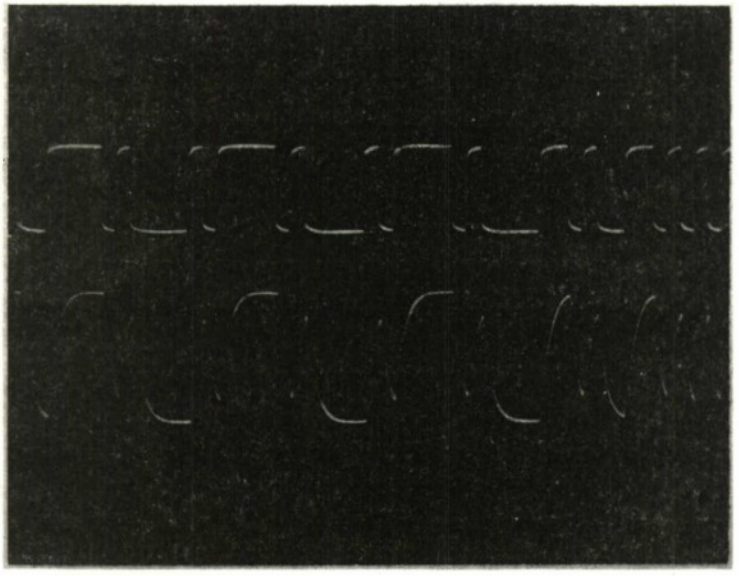

Figure 12. Polar NRZ Signal Transmitted at 2400 bits/second Over an 8-mile 19 AWG Non-loaded Line (vertical scale, top trace: 10 volts/division; vertical scale, bottom trace: 2 volts/division; horizontal scale: 2 milliseconds/division.)

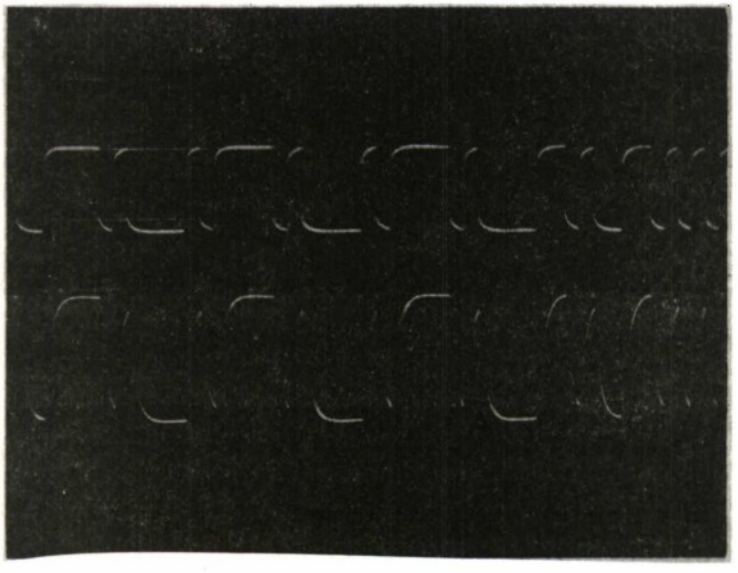

Figure 13. Polar NRZ Signal Transmitted at 2400 bits/second Over an 11-mile 19 AWG Non-loaded Line. (vertical scale, top trace: 10 volts/division; vertical scale, bottom trace: 2 volts/division; horizontal scale: 2 milliseconds/division.)

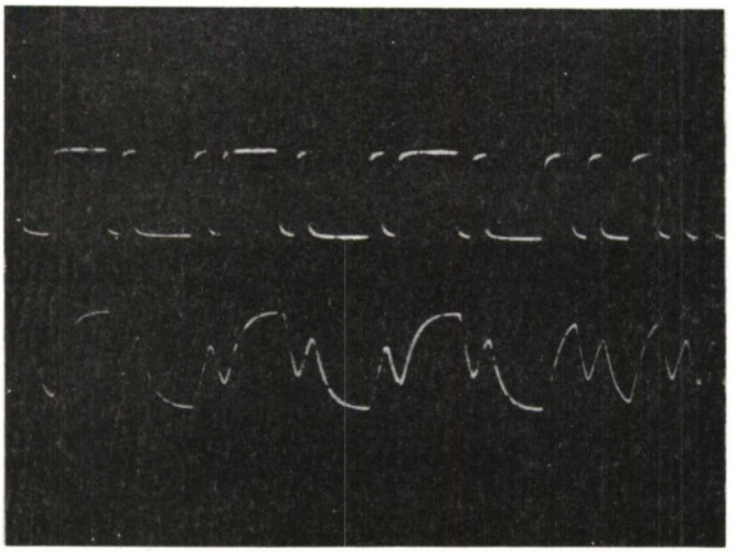

Figure 14. Polar NRZ Signal Transmitted at 2400 bits/second Over a 13-mile 19 AWG Non-loaded Line. (Vertical scale, top trace: 10 volts/division; vertical scale, bottom trace: 0.5 volt/division; horizontal scale: 2 milliseconds/division.)

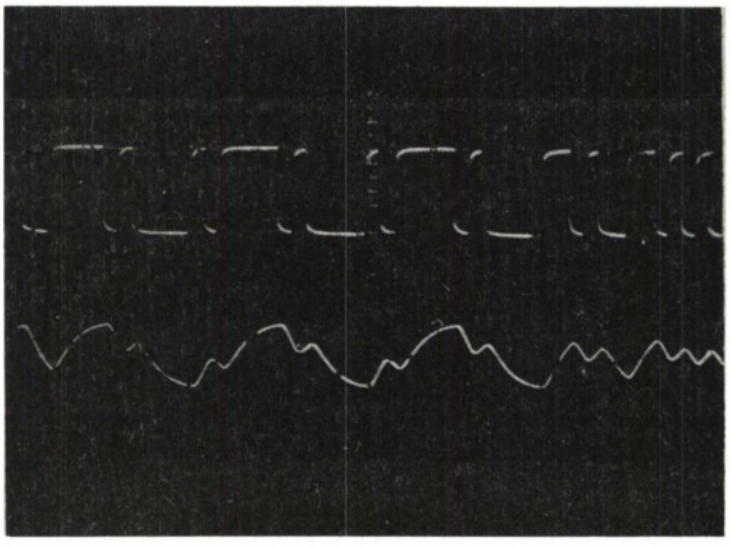

Figure 15. Polar NRZ Signal Transmitted at 2400 bits/second Over a 16-mile 19 AWG Non-loaded Line. (Vertical scale, top trace: 10 volts/division; vertical scale, bottom trace: 2 volts/division; horizontal scale: 2 milliseconds/division.)

A POSSIBLE MODIFICATION

The primary disadvantage of the system just discussed is that separate pairs are required for data and timing. Although the cost of 22 and 19 AWG pairs is not great it may be desirable to conserve cable plant, especially with a large number of subscribers and many distant subscribers. One possibility of solving this problem is evident from an examination of the polar NRZ power spectrum with the clock signal power spectrum superimposed, as shown in Figure 16. The clock frequency is 1/T, which occurs at the first null of the polar NRZ spectrum. The relative position of the clock signal spectrum is such that the data and clock should be easily separable without significant distortion to either. This fact can be utilized so that the system will require one 2-wire pair per duplex subscriber.

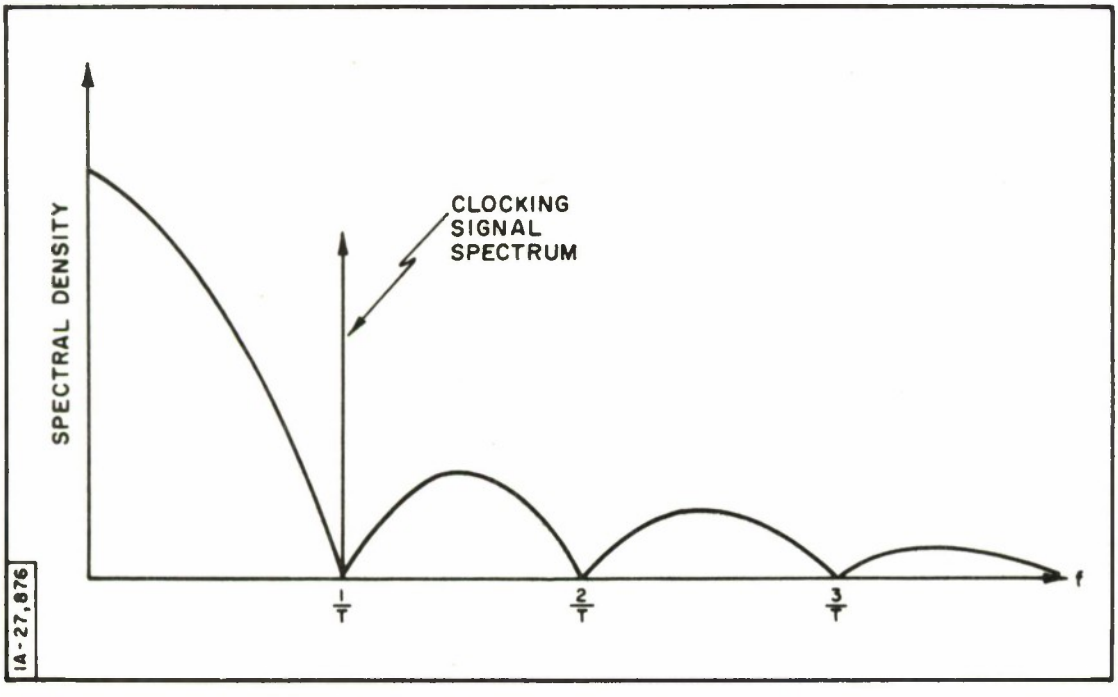

Figure 16. Superposition of Polar NRZ and Clocking Signal Power Spectra

SECTION IV

TECHNIQUES FOR HIGHER DATA RATES AND LONGER LINES

The results presented in Section II show that for the higher data rates the useful transmission range for polar NRZ signals is rather limited. However, the useful transmission distance can be increased to any desired distance by employing baseband regenerative repeaters. A baseband signaling method which is more suitable for transmission over non-loaded wireline pairs at higher data rates than polar NRZ is bipolar signaling. At the same time, the implementation of a bipolar regenerative repeater is simpler.

A bipolar NRZ signal is essentially a ternary signal in which one binary symbol is coded as a zero voltage level and the other binary symbol is alternately coded as +V and then -V voltage levels. The power spectrum of this signal for a random data sequence is given by:[5]

$$\Phi_p(f) = \frac{V^2}{4\pi^3 f^2 T}\left(\frac{3}{4} - \cos 2\pi fT + \frac{1}{4}\cos 4\pi fT\right) . \qquad (5)$$

The peak of the bipolar NRZ power spectrum occurs at a frequency $f = \frac{1}{2T}$, where T is the signaling interval. The power spectrum has zeros at dc and frequencies equal to multiples of the signaling interval. If the bipolar signal is used with a 50 percent duty cycle, the peak of the spectrum occurs at a frequency equal to the reciprocal of the signaling rate, and zeros at dc and frequency equal to multiples of twice the signaling interval. Bipolar NRZ and bipolar RZ signals and their spectra are shown in Figure 17.

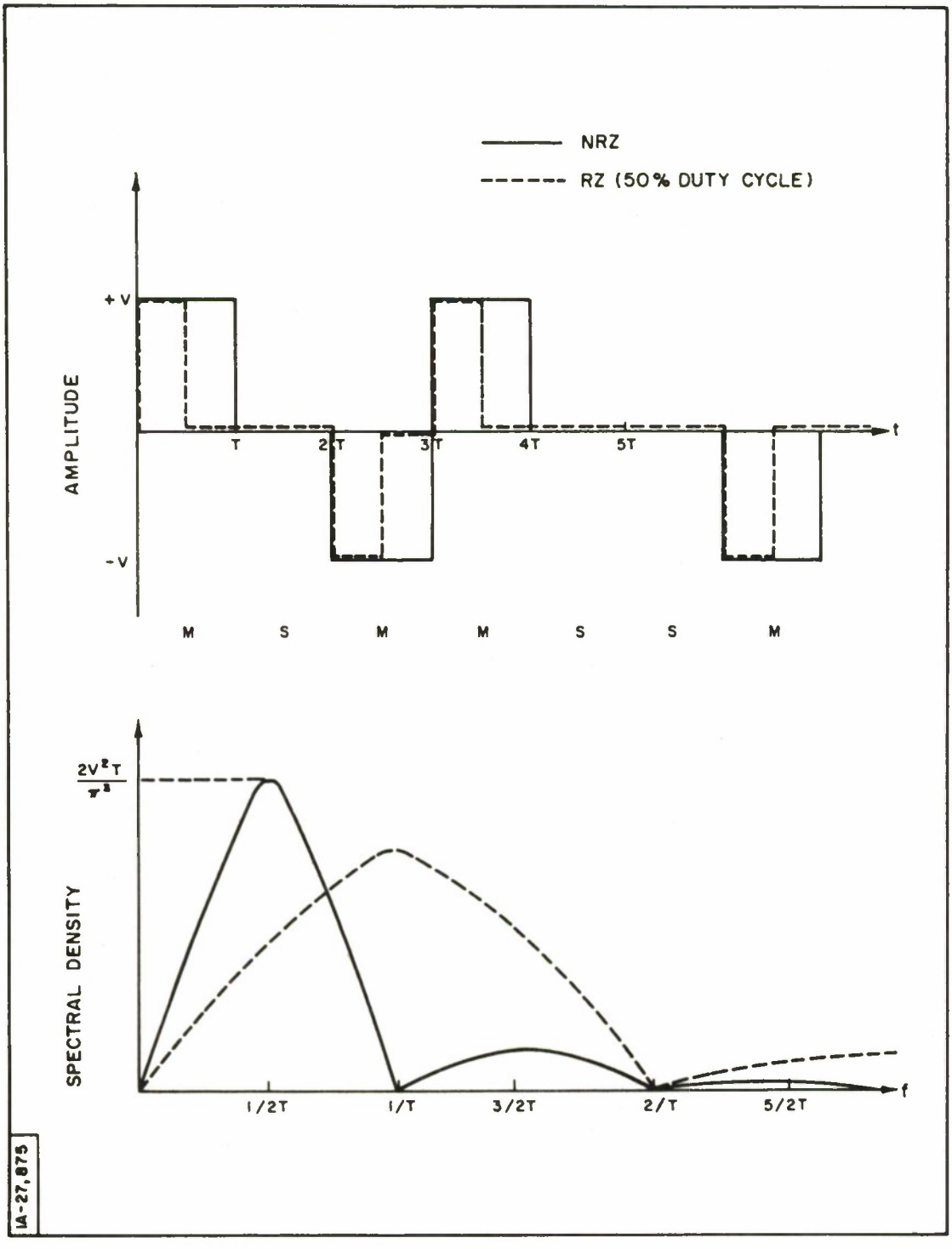

Figure 17. Bipolar Signals and Their Power Spectra

Several coding techniques which yield power spectra similar to those of bipolar signals are known and have been employed. These signals are more suitable for high data rate transmission than polar signaling since, as the data rate increases, the frequency at which the peak of their power spectra occurs increases. At the same time, the attenuation of the non-loaded wire pairs increases, but the distortion decreases with increasing frequency. The increased attenuation is easily overcome with power.

The regenerative repeater is simpler to implement for bipolar RZ (with 50 percent duty cycle) than polar, since the spectrum peak of the former occurs at the clocking frequency, from which the repeater clock can be easily derived.

At low data rates the bipolar signaling technique offers no real advantage over polar signaling since the spectra peaks are essentially coincident. Also, because bipolar signaling attempts to discriminate between 0 and V whereas the polar technique discriminates between +V and -V, bipolar signaling has a 3 dB poorer margin against noise.

The bipolar technique has been widely used. Probably the most well known application is the T1 carrier system[4, 5, 6] which transmits a bipolar RZ signal at 1.5 Mb/s rate over 22 AWG non-loaded wire pairs. The repeater spacing for the system is 1 mile. Other applications are known in which bipolar-related signals at 50 kb/s have been transmitted successfully over ranges of better than 10 miles over 19 AWG non-loaded pairs.

A bipolar system with several repeaters can be easily implemented for applications similar to the one presented for polar signaling, using

some of the implementation ideas proposed for the T1 carrier system. (See References 5 and 6.) The only other consideration to take into account is that it may be desirable to establish the detection threshold at the repeater from the received signal. This can easily be done with a long time-constant averaging circuit.

SECTION V
CONCLUSIONS

The theoretical and experimental results presented in this paper show that significant transmission distances over non-loaded wire pairs can be achieved by using polar NRZ signaling. This fact can be used to effect a considerable cost savings in implementing data transmission systems which have short-haul data transmission requirements. Polar NRZ signaling techniques can be employed over these links with simple and inexpensive implementation methods instead of the more conventional but more expensive carrier transmission techniques.

For long links and/or links for transmitting high data rates, the bipolar signaling technique can be employed with several regenerative repeaters more effectively than polar signaling yet still less expensively than carrier transmission techniques. Only for the extremely long transmission distances will carrier transmission techniques prove to be the most cost-effective approach. It is urged that baseband techniques be given careful consideration in designing data transmission systems which may have a significant number of links with short-haul requirements.

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13. ABSTRACT

The feasibility of using baseband signaling techniques for data transmission over multipair wireline cable plant is examined. The limit of transmission distance over 19 AWG and 22 AWG non-loaded wire pairs is determined by computing the eye patterns for polar NRZ signaling for various data rates. Polar NRZ signaling was implemented and tested on existing wireline data transmission links, and results were compared with theoretical predictions. The results showed that significant transmission distances can be achieved by using simple and inexpensive polar NRZ techniques. Other baseband techniques such as bipolar signaling at described and recommended as candidates for extremely long multipair wireline cable links and/or high data rate transmission.

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